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Neutron Detectors Array System for ICF Experiments

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Abstract

A very Sensitive Neutron Spectrometer (SNS) is designed for SG-III prototype laser facility in China. The spectrometer consists of a 960 channel single-neutron-interaction detector array placed 16.67m from the Inertial Confinement Fusion (ICF) target. Each detector channel has a plastic scintillator coupled to a photomultiplier tube followed by a discriminator, shaper, TDC and ADC to allow the measurement of neutron arrival time as well as pulse amplitude. The array is capable of measuring yields as low as 4×10^5 neutrons (100 detected hits) with resolution of 1.0 ns (90keV for 14-MeV neutrons with 16.67m flight path). Details of design and testing will be presented.

Keywords: ICF; neutron spectrum; time-of-flight

1. Introduction

ICF is a branch of fusion energy research, and its goal is to achieve clean and permanent energy solution. In recent years, the increasing neutron yields of ICF implosions have made possible to attempt measurements of low probability, neutron producing secondary reactions. The yields from these secondary reactions are typically several orders of magnitude less than the primary neutron yields, necessitating the use of a very sensitive neutron detector. For these applications, neutron energy spectroscopy with good energy resolution is also required. Finally, stringent shielding and geometry requirements are necessary to distinguish the small component of secondary neutron from the background produced by the primary neutrons and high-energy photons. [1]

The neutron energy spectrum from ICF targets provides information about the reacting deuterium or tritium ions. For example, the spectrum may be used to diagnose the temperature or area density (ρR) of the fuel. Because the neutron emission time is short (<1 ns), the spectrum can be obtained from time-of-flight (TOF) measurements. In many ICF targets, the yield is too low for accurate spectra from conventional current-mode TOF detectors. Single-hit neutron detector arrays are used to increase

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sensitivity while maintaining good time resolution for low-yield targets. [2] The spectrum can be obtained from the arrival time distribution of individual neutron interactions in the multi-channel detector array. That's the principle of SNS.

2. Neutron producing reactions

When the ICF fusion target in laser facility is filled with pure deuterium gas, the DD reaction has two nearly equal branches:

$$D + D \rightarrow p + T(1.01MeV) \tag{1}$$

$$D + D \rightarrow n(2.45MeV) + {}^{3}He \tag{2}$$

The triton (T) produced in the first branch has 1.01MeV, and has a finite chance of reacting with a fuel deuteron to produce a secondary neutron. In nowadays ICF experiments, the ρR is high and the triton could slow to thermal energies on the way out of the fuel. In these cases, the faster the slowing rate, the fewer the secondary neutrons produced. So secondary neutron yield and spectrum will help accomplish the ρR diagnostics.

$$D + T(<1.01MeV) \rightarrow n(11.8\sim17.1MeV) + \alpha \tag{3}$$

Single-hit neutron detector arrays have been used in several facilities to characterize ICF implosions either by measuring the yield from deuterated plastic capsule implosions or by measuring the energy spectra of secondary neutrons produced in moderate convergence implosions. [3-5]

3. Detector description

The SNS detector is an array of 960 individual detectors. It's designed to obtain neutron spectra from targets on SG-III prototype laser fusion facility in China. [6] It can measure the secondary neutron spectrum with 90keV energy resolution for target yield low to 4×10^{5} by using scintillators, which means that the time resolution is about 1.0 ns. [1,4]

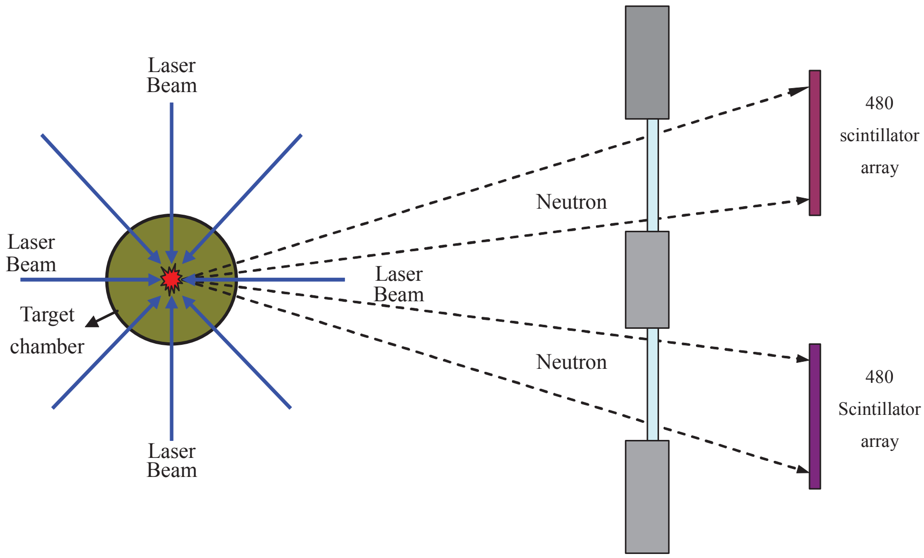

Fig. 1. The detectors array system is separated into two parts

The SNS detector is separated into two 480-channel parts, which is shown in Fig.1. The two parts are placed in different angles, allowing the investigation of the anisotropy of neutron production. The fundamental specifications of the detectors array are shown in Table 1.

Table 1. Fundamental specifications of the detectors array

Parameter	Value
Scintillator volume (total)(cm^3)	7.9×10^5
Flight path (m)	16.67
Geogmetrical efficiency: $\eta_g=\Omega_{detector}/4\pi$	2.16×10^{-3}
Intrinsic detection efficiency: η_i (%)	20 for DT neutrons
Detection efficiency: $\eta_{dd}=\eta_g\times\eta_i$	4.32×10^{-4}
Energy resolution (FWHM in keV)	90 for DT neutrons

The SNS detector is placed 16.67m from the center of the ICF target chamber. And there has a 4-centimeter-thick lead shield mounted between two 1-centimeter-thick iron boards in front of each scintillators array to reduce high energy photon, X rays, and γ rays backgrounds.

The whole array is divided into 60 sets of 16-channel detectors. Each detector has a 4 inches diameter × 4 inches thickness columniform plastic scintillator. Each scintillator is coupled to a photomultiplier tube (PMT). The PMT is a linearly focused type electron multiplier with 1.5 inches photocathode. And the pulse from the PMT is connected to the following electronics system, in the front of which is a leading edge timing discriminator.

The detection timings are picked up by these discriminators. But the pulse amplitude from the PMT has a very wide-up to 1000-dynamic range, which would cause very heavy time walk effect in the leading edge discriminator. So the pulse amplitude should also be measured simultaneously. On this condition, it is needed for the discriminator to have a logic output and an analog output. The analog output of the discriminator is sent to an amplitude measuring unit including a pulse shaper module and a gated ADC module. And the logic output is sent to a multi-hit TDC module. The flight times and velocities for gamma rays and several different neutrons from the center of the target chamber are shown in Table 2. The measurement range of the TDC should be at least 1000 ns and covers the entire region of interest, from shot time to the arrival of 2.45MeV primary neutrons from a pure deuterium target.

Table 2. Flight times of gamma ray and different neutrons arrived at the detectors array

species	energy/MeV	velocity/($cm\cdot ns^{-1}$)	flight path/m	flight time/ns
gamma rays	any	29.98	16.67	55.60
secondary neutrons(high)	17.1	5.64	16.67	295.57
D-T neutrons	14.05	5.14	16.67	324.32
secondary neutrons(low)	11.8	4.71	16.67	353.93
D-D neutrons	2.45	2.16	16.67	771.76

A complete detection channel consists of a scintillator, a PMT, a leading edge discriminator unit, [7] a pulse shaper unit, an ADC unit and a TDC unit. [8] Since the total time resolution of the measured time-of-flight spectrum of the detectors array is 1.0 ns, the overall time resolution of the electronics system is asking 100 ps. It is a critical requirement for multi-channel systems and the design based on the standard VME bus will help to accomplish it. Furthermore, every 16 units of the same function can be integrated in a VME 6U board. Thus, a 16-channel detectors and electronics system can be designed based on VME crate and bus, as is shown in Fig 2.

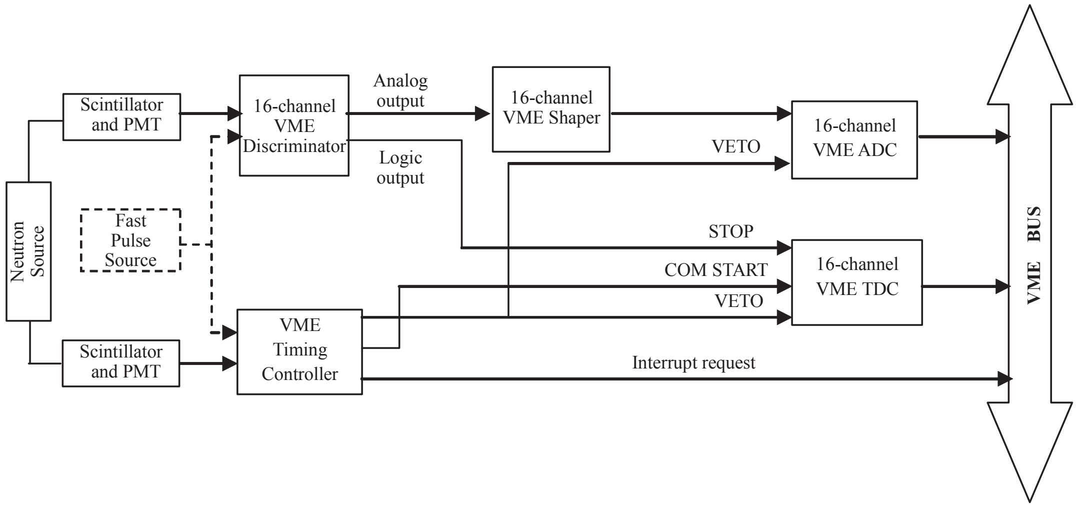

Fig. 2. The schematic of 16-channel detectors and electronics

In ICF implosions, many particles will be produced, including X rays, gamma rays, secondary neutrons and primary neutrons. They arrive at the detectors array at different times. This is why a TOF can be used. But the TOF detector operated in single-hit mode, which means, once a detection channel received a particle and measured the amplitude and arrival time, other particles will be rejected. And the X rays, gamma rays which will arrive before the interested secondary neutrons can not be shielded completely. On the other hand, the secondary neutron yield is several orders less than the primary neutron yield, and the neutron spectrometer will be able to measure the energy distribution but will saturate before the arrival of the primary neutrons. To ensure the proper functioning of the neutron spectrometer, a timing controller module is needed. It will supply relevant control signals for the electronics system. [9]

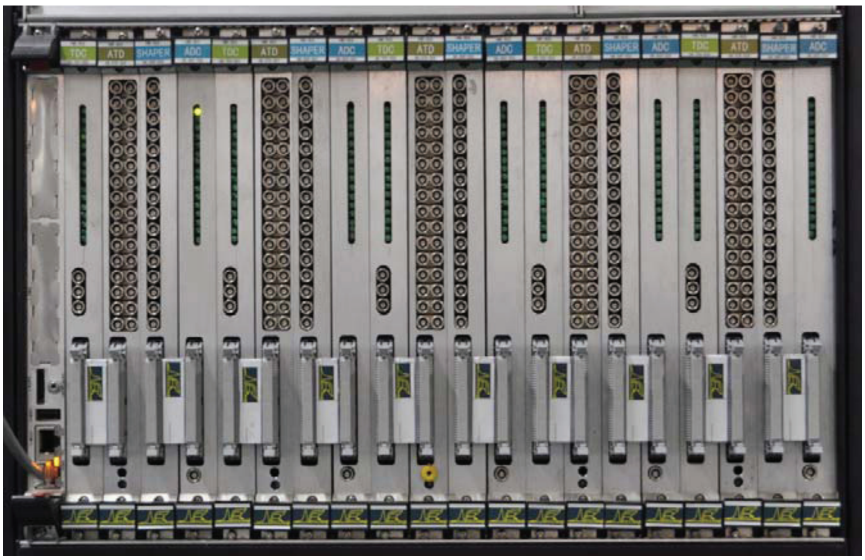

Fig. 3 The 80-channel SNS system

4. Test results

An 80-channel little SNS system has been completed. It consists of 5 sets of basic 16-channel detector and electronics system, which is shown in Fig. 3. All the 80 channels have been tested, including electronics test and cosmic ray test with detectors. The electronics test shows that the electronics system has a time resolution of less than 61 ps. [8] The cosmic ray test results indicate that after correction, the total time resolution (with detectors) can achieve to about 500~700ps. Recovery time for an individual channel is dependent upon the detected event pulse amplitude but is generally 35 ns. [10] A typical cosmic ray test result is shown in Fig. 4.

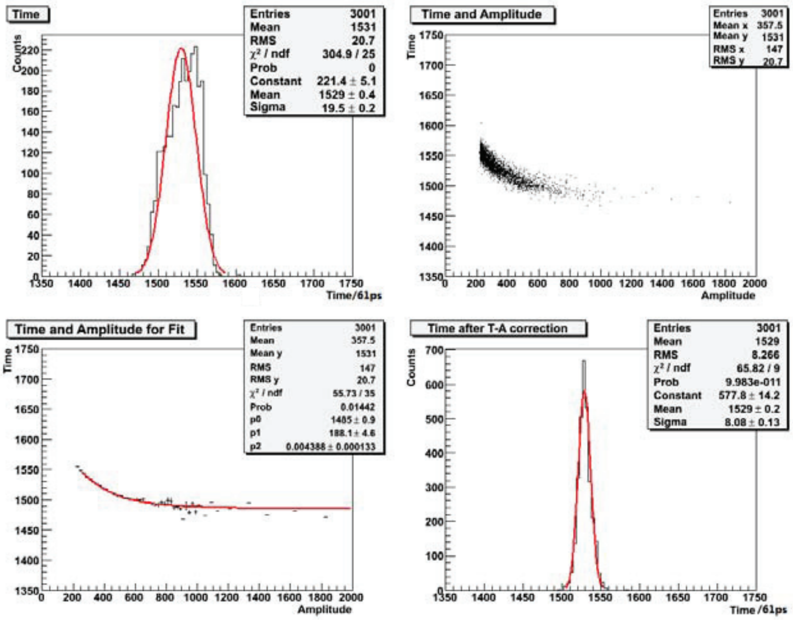

Fig. 4 Typical result of cosmic ray tests with detectors

5. Conclusion

The SNS detector has provided a measurement method of the secondary neutron spectra of ICF implosions at SG-III prototype. The whole 960-channel SNS is under construction and will be completed in late 2012. The future work will be the experimental research in SG-III prototype facility.

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